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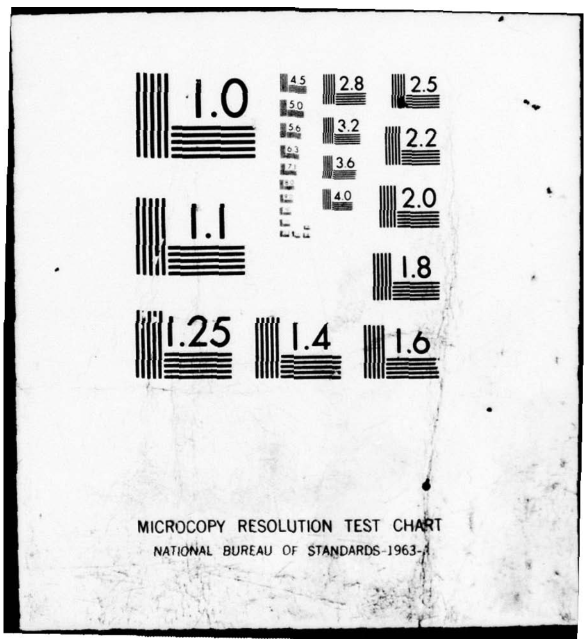
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Ultrasonic Data Link Measurements

by
Myren L. Iverson
Fuze and Sensors Department

MARCH 1979

NAVAL WEAPONS CENTER
CHINA LAKE, CALIFORNIA 93555

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FOREWORD

The ultrasonic data link concept described in this report will provide a link through a ship's structure between warning sensors and a ship's damage control center that is uninterruptible by fires or explosions. This concept is also compatible with other proposed data bus concepts and allows for graceful degradation. Included are the results of measurements made aboard Navy and Coast Guard ships of several important parameters that affect the ultrasonic data link performance.

The work was performed during the period from October 1977 through September 1978 and was supported by the NAVMAT Block, Damage Control/Personal Survival, Task No. ZF43451. This report was reviewed for technical accuracy by Ken LaBaw of the Naval Weapons Center.

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~~(U)~~ The ultrasonic data link concept described in this report will provide a link through a ship's structure between warning sensors and a ship's damage control center that is uninterruptible by fires or explosions. This concept is also compatible with other proposed data bus concepts and allows for graceful degradation. Included are the results of measurements made aboard Navy and Coast Guard ships of several important parameters that affect the ultrasonic data link performance.

LEVEL II

CONTENTS

INTRODUCTION

During the initial investigation of the feasibility of using an ultrasonic data link to transmit fire sensor data through steel structures within a ship, several parameters were identified on which information was lacking. Although ultrasonics have been studied for many years, some applications are recent developments. As a result there is very little literature that applies to this application even though much is available in related areas.

There are reports on underwater communications, but not through steel; on absorption and propagation in water, but very little in steel and none in large structures; on noise levels aboard ships at low frequencies, but not at frequencies above 100 kHz. To fill these gaps, measurements were made aboard ships and in the laboratory on the steel structures. Data were gathered on the background noise levels of several ship engine types and other noise sources. Acoustic coupling techniques were investigated for use on ships. Multipath interference for ultrasonic waves traveling in large structures were characterized. Scattering and absorption losses were also measured.

REPORT CONTENT

This report describes requirements for the data and methods used to obtain them. There are also enlightening comments on some of the problems that are encountered in making ultrasonic measurements. Test setups, results, and conclusions are included.

The background noise measurements indicated that above 300 kHz only the diesel engines contributed significantly to the noise and that between 100 kHz and 300 kHz the gas turbines and steam turbines were 100 times quieter than the diesel engines. There were other sources that generated large short-duration spikes. Investigation of multipath interference indicated that other than simple processing would be required to achieve data rates exceeding 100 bits/s/channel. Scattering losses aboard ship were higher than in the laboratory structure and limited the practical transmission distance to 150 feet. This limit was sufficient for the damage-control concept described in this report. Several reliable coupling methods were adopted from acoustic emission technology.

Based on the findings, a model of the link incorporating a coding and modulation scheme that uses a linear FM sweep, band limited noise or some other spread-spectrum technique should be built and tested aboard ship. After making any necessary improvements, a concept design similar to the approach described in this report should be developed.

TRANSDUCER RESPONSE STANDARDIZATION

The ultrasonic band from 100 kHz to 1 MHz which is being considered for a ship data link is also the band used for fish finders, shallow water depth sounders, and nondestructive testing. Therefore, many transducers and many items of related equipment are available from several manufacturers. Since nondestructive testing (acoustic emission technology) is used mostly on steel structures, it is of interest and value to the ultrasonic data link program. In the literature, there are many papers on transducer design, acoustic emission, and coupling especially into surface wave devices, and underwater applications. One outstanding deficiency is a uniform or meaningful transducer spectral sensitivity measurement method. Most manufacturers use a methcd developed at the Lawrence Livermore Laboratories,[1] where a *known* traceable transducer pair is used. One transducer is always used as the source and the other as a receiver. The transducers are placed face to face with a couplant between them and the spectral response is compared to the previously recorded spectral plot to assure that the source has not changed. Then the unknown transducer replaces the known receiver. The output spectral plot is corrected based on the known response of the reference pair and then recorded as an absolute sensitivity.

Even if the response of the reference pair is known precisely, coupling a transducer to any other medium changes its characteristics, both electrically and mechanically. With this method, the source transducer is driven with a sine wave. Since the transducer element thickness and the quarter-wave matching face plates have dimensions on the order of a wavelength, standing waves are set up between the source and the unknown transducer causing resonances due to transducer dimensions. When the transducer is coupled to a structure, different resonances result. (A transducer input admittance diagram over a band of frequencies changes drastically when coupled to a structure.)

One manufacturer of acoustic emission equipment has developed a method called the spark gap method to determine transducer sensitivity. Since the spark is short in duration the pressure wave it generates has a broad band of frequency components, thus approximating an acoustic emission event. The pressure wave is coupled into an aluminum bar on which the transducer under test is coupled. The bar dimensions are large to suppress multimode Lamb waves and makes the arrival of the Rayleigh (surface) waves separable. The transducer output is amplified and its spectral response to the Rayleigh wave is recorded using a spectrum analyzer or with a tunable narrow-band filter. This technique is probably the best because an attempt has been made to consider the dimensions of the structure. However, the transducer's response is still dependent on the coupling. Errors in the spectral response of a transducer affect the accuracies of the measurements discussed in this report.

[1] Dunegan/Endevco. *Acoustic Emission Transducer Calibration–Transient Pulse Method*, by Robert L. Bell. Livermore, CA, DE, February 1973. (Technical Report DE-73-3.)

DATA REQUIREMENTS

In order to predict the performance of an ultrasonic data link, the background noise level, the attenuation, the multipath interference effects, and the coupling must be investigated. A literature search yielded little information applicable to this project. Noise measurements have been made at lower frequencies of ship engines and propellers. Mason[2] and others who cite Mason, give some data on attentuation at higher frequencies in steel. Multipath interference is discussed for sonar and underwater communication applications. Coupling into surface wave devices and into water are treated by several authors[3] but, generally, scant information is available for this application.

To obtain the necessary data, measurements were made aboard Navy and Coast Guard ships, and in the laboratory. Background noise aboard ship comes from the engines, generators, compressors, equipment, tools, personnel and weapons. Data were gathered on three types of engines: steam turbines, gas turbines, and diesel. Noise levels from generators, compressors, tools, equipment, and personnel were also recorded. The noise level from a missile firing was observed but not recorded. Attenuation was investigated aboard ship and in the laboratory as was the multipath interference. Coupling, with the exception of coupling a signal into the water, was studied in the laboratory since ships were not as available. No differences are expected, however. Coupling into the water will be addressed later in the project.

SHIP MEASUREMENTS

Ultrasonic background noise measurements were made on board two ships. One ship had steam turbines while the other had two gas turbines and two diesel engines.

TIME DOMAIN NOISE MEASUREMENTS

Data were taken in both the time and frequency domains. For the time-domain measurements, the equipment was set up as in Figure 1. The function generator and ultrasonic source were used only to verify good coupling for the initial setup. Since the intent was to measure the noise variations with time for several frequency bands, a bandpass filter was used. Two different transducers were used: S140B narrowband transducer (120-170 kHz) and FC500 broadband transducer (100-1000 kHz).

Figure 2 is a plot of the noise versus time in the engine room. The spikes are a result of something striking the structure like chipping hammers or tools being dropped. The impulse effects can be eliminated by detecting out-of-band noise and gating the in-band signal off during the impulse. Since they are short in duration (< 1 ms), gating will not affect data transmission. Also of interest are the variations in the

[2] Mason, W. *Physical Acoustics and the Properties of Solids.* Princeton, NJ, Van Nostrand, 1958.

[3] Bertoni, Henry, and Theodor Tamir. "Characteristics of Wedge Transducers for Acoustic Surface Waves," *IEEE Transactions on Sonics and Ultrasonics*, Vol. SV-22, No. 6, November 1975, pp. 415-420.

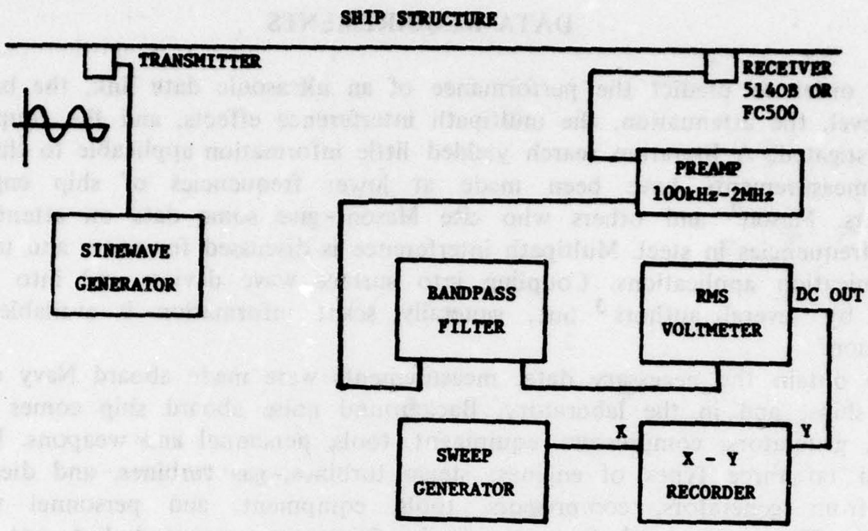


FIGURE 1. Time Domain Noise Measurements. The sinewave generator and transmitter are used to check coupling only.

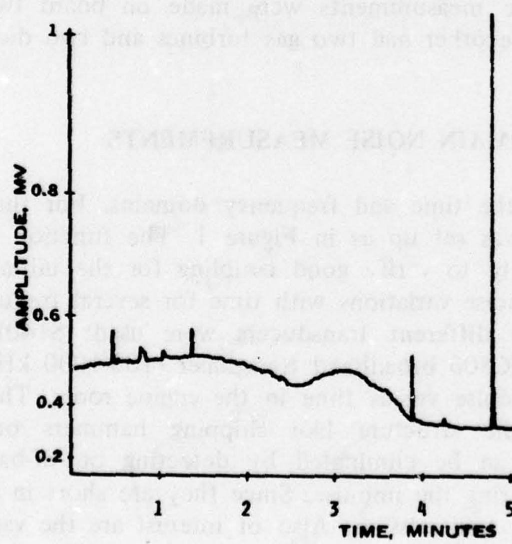


FIGURE 2. Typical Time Variations of RMS Noise Amplitude for the Ultrasonic Band From 140-160 kHz (Using the S140B Transducer) Overhead in the Engine Room.

noise *floor*. This variation was noticeable in the audio band, and appeared to be caused by a steam relief valve near the transducer. Figure 3 is another plot in the same band at a different time. The transducer was located under the deck of a machine shop where a large piece of steel was being machined. Again the spikes can be processed out. Figure 4 is another plot taken with the transducer attached to the steam turbine support while underway at standard speed. Since data were taken on a not-to-interfere basis and no changes in speed were planned, only standard engine speed was available.

FREQUENCY DOMAIN NOISE MEASUREMENTS

The setup for the frequency domain measurements is shown in Figure 5. Here the sinewave generator and ultrasonic source provided a reference in addition to the zero frequency reference on the spectrum analyzer as well as an indication of the coupling quality. Two different transducers were used as receivers: FC500 broadband and the AC175 (130-180 kHz) narrowband. The spectrum analyzer has a passband from 1 kHz to 1.8GHz, but only the range to 1 MHz was used. Figures 6 through 8 are photographs of the spectrum analyzer output trace showing the noise peak voltage as a function of frequency for a diesel engine and a gas turbine at different speeds. The width of the traces are due to the sporadic nature of the noise. With the sweep/rate of 10 kHz/s there was little averaging of the noise. A video filter (10 Hz bandwidth) was available for filtering the output before displaying. The filtered output approximates an RMS voltage and is superimposed on Figures 6c and 7c. (The transducer and the preamplifier responses must also be considered in order to accurately represent the noise spectrum.)

As noted in Figures 6 through 8, the transducers were located on the engine supports. Figure 9 is a series of photographs of the traces taken with the transducers located overhead (see Figure 10) in the next compartment forward of the engine room. Here the noise amplitude is lower. The overhead structure in the engine room also had a lower noise amplitude than on the engine supports. This may be due either to the fact that the engine supports are coupled to the hull and that the water may be severely damping the noise, or that the noise is dispersed throughout the ship via the hull making the intensity lower, or both.

In analyzing the data, it is convenient to first divide the spectrum of interest into bands based on transducer and preamplifier responses. Three bands seem most appropriate: below 100 kHz, 100 kHz to 400 kHz, and 400 kHz to 1 MHz. Below 100 kHz the preamplifier and both transducers are "rolling off": the preamplifier at a 12 dB/octave rate, the FC500[4] transducer at a 6 dB/octave rate, and the AC175[5] fluctuating 20 dB between peaks with a general decrease of 6 dB/octave. In addition, the FC500 is 20 dB down at 100 kHz. (Although these sensitivity measurements have not been made by the manufacturer below 100 kHz, gross measurements were made in the laboratory.) In the trace photographs the noise amplitude below 100 kHz is not

[4] Acoustic Emissions Technology Incorporated. "Model FC500 Data Sheet," Sacramento, CA, 1976.
[5] Acoustic Emissions Technology Incorporated. "Model AC175 Data Sheet," Sacramento, CA, 1976.

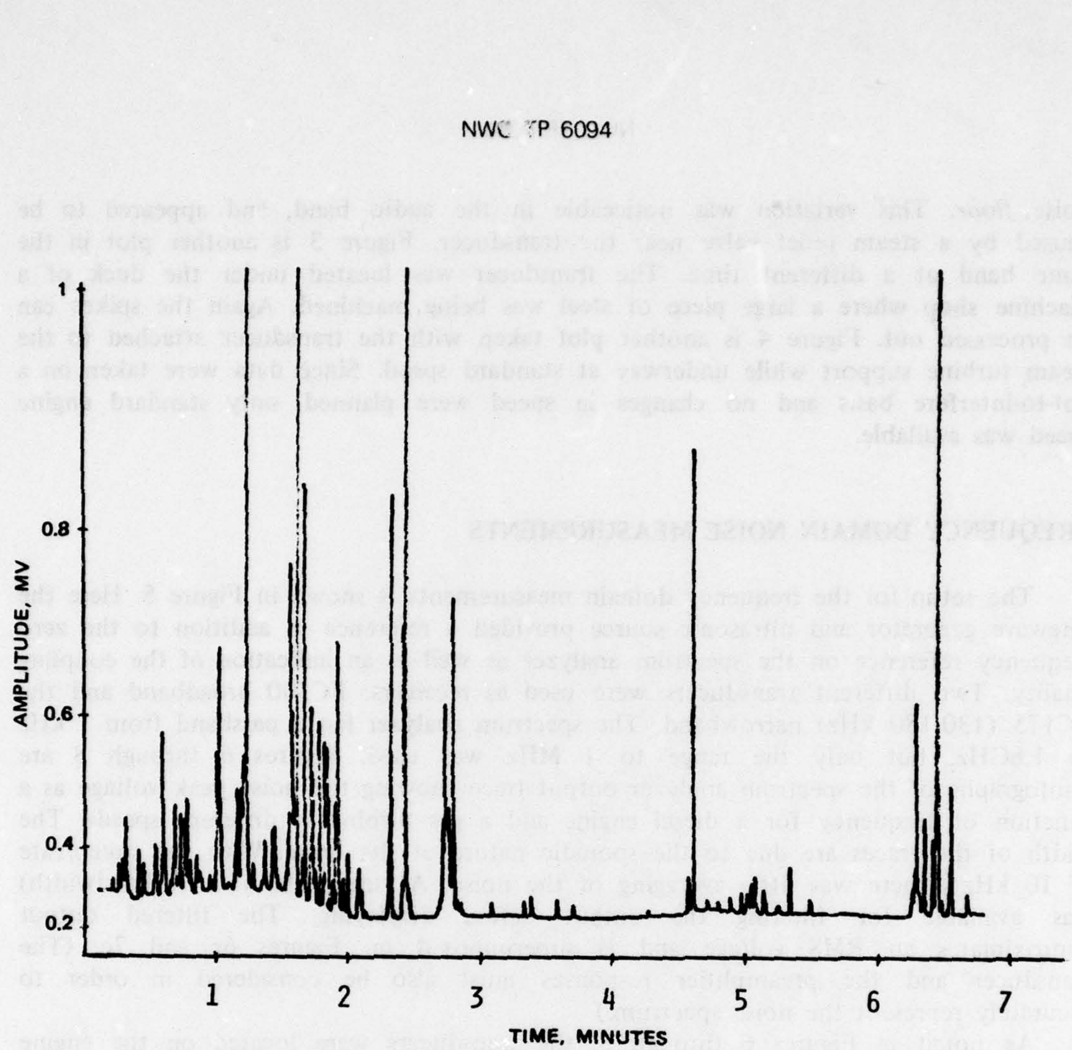


FIGURE 3. Typical Time Variations of the RMS Noise Amplitude for the Ultrasonic Band From 140-160 kHz (Using the S140B Transducer) Below a Machine Shop Work Bench.

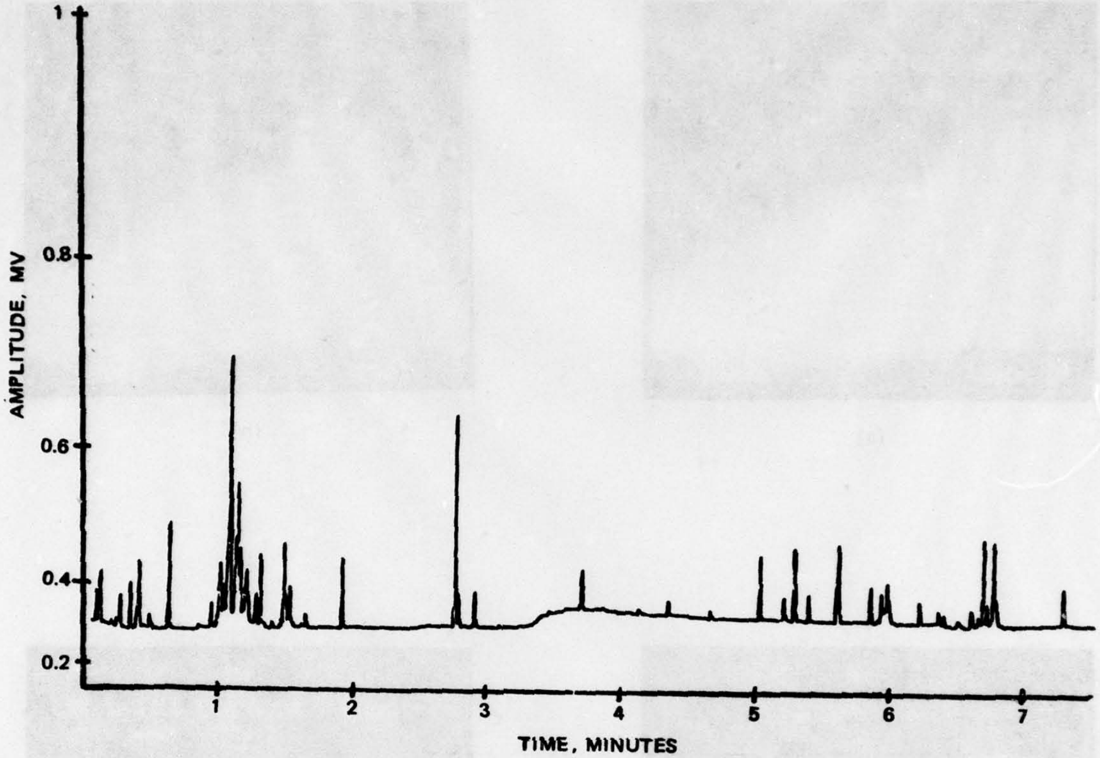


FIGURE 4. Time Variations of the RMS Noise Amplitude for the Ultrasonic Band From 140-160 kHz (Using the S140B Transducer) on the Engine Support of a Steam Turbine.

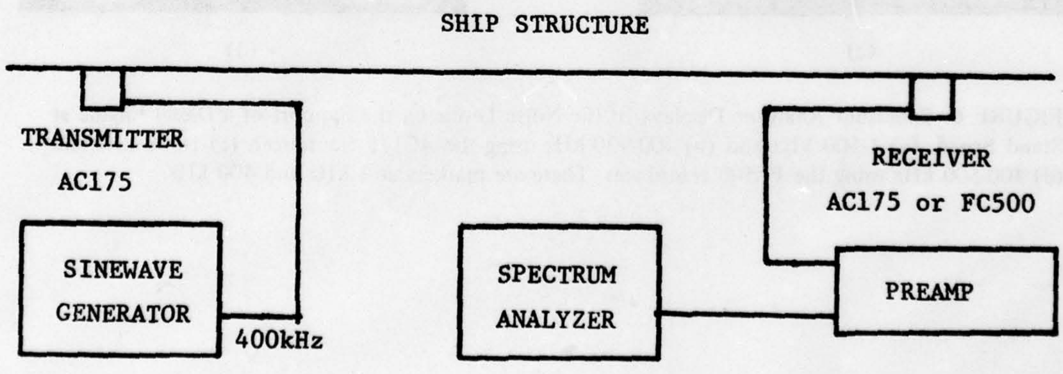


FIGURE 5. Frequency Domain Measurements. The generator and transmitter provide an additional reference.

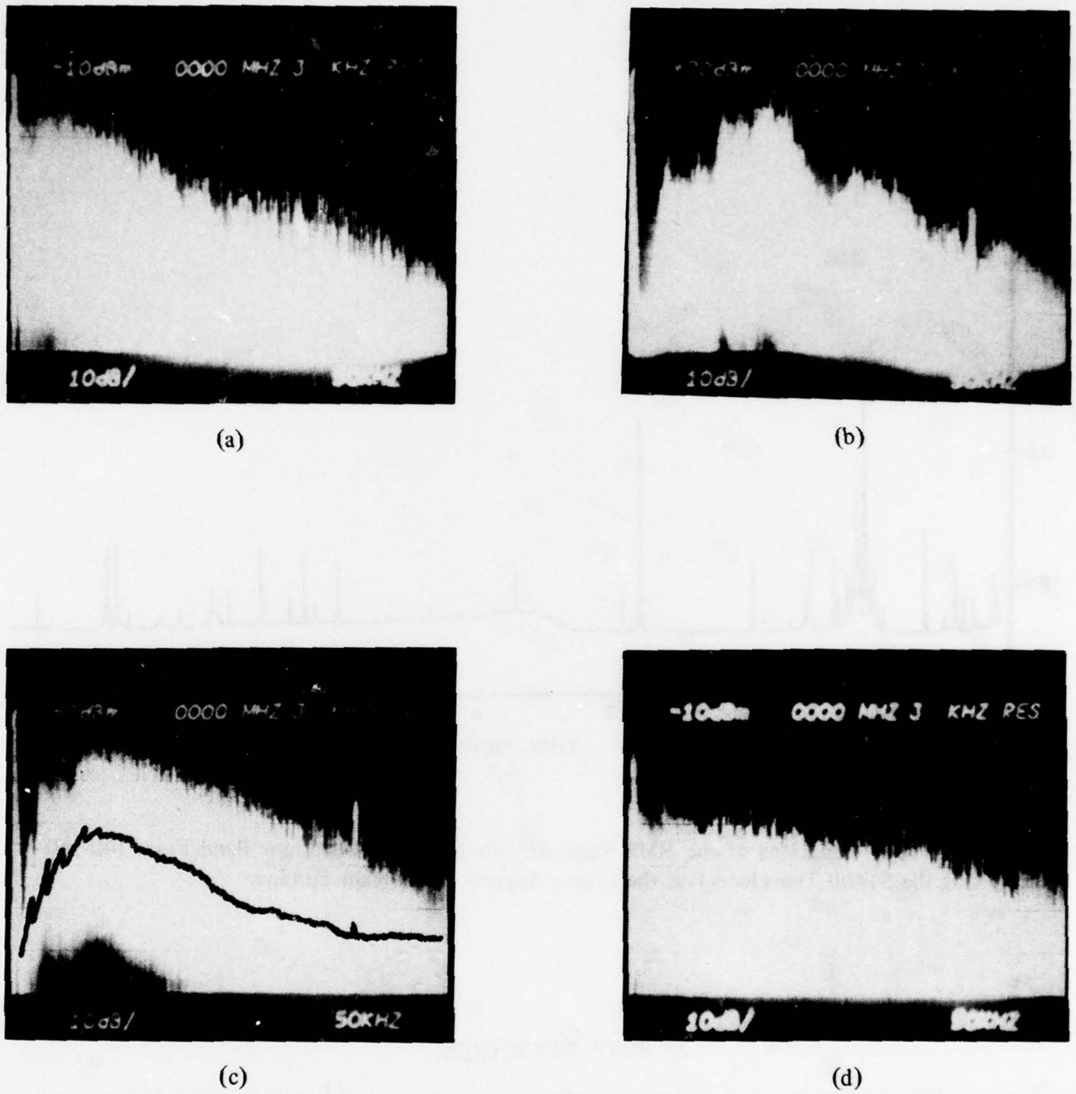
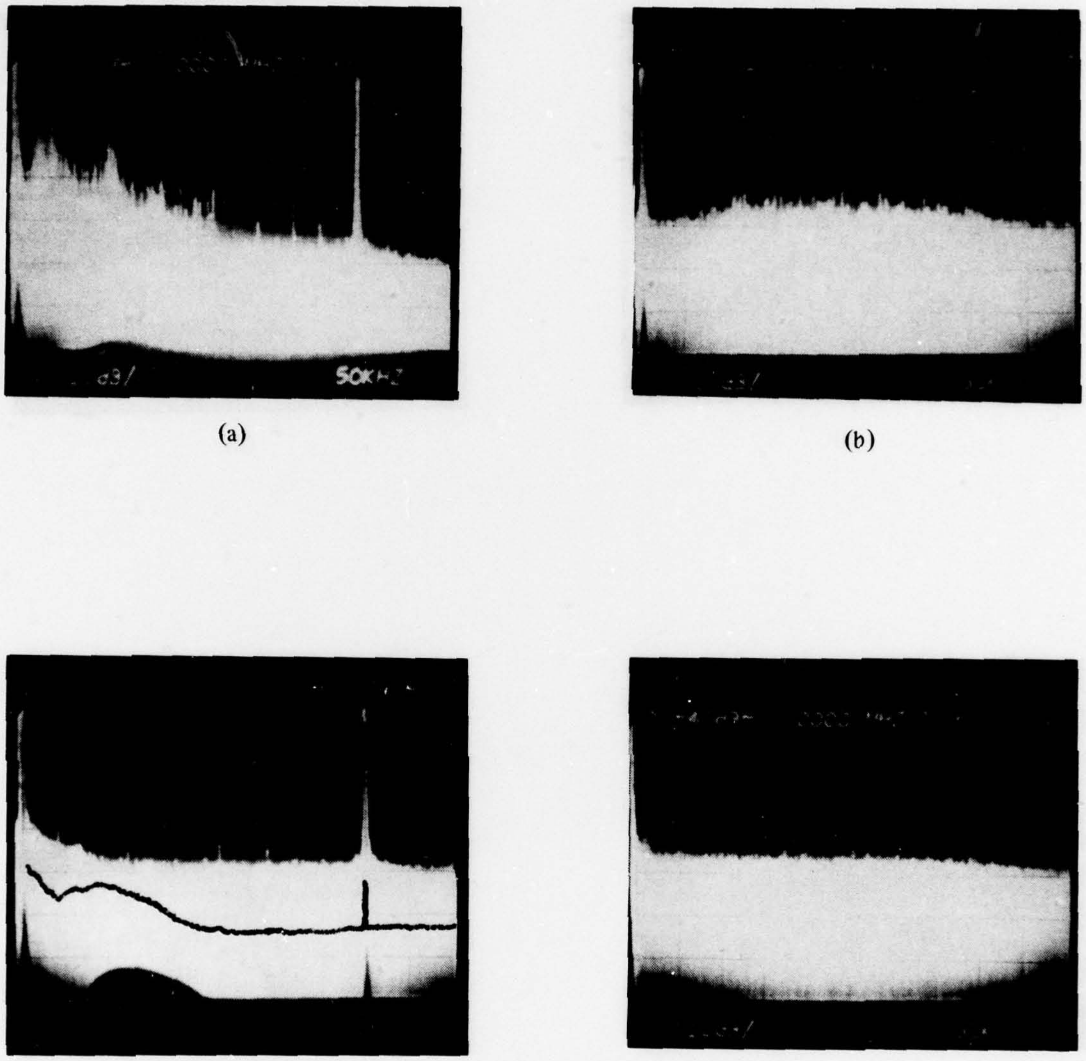


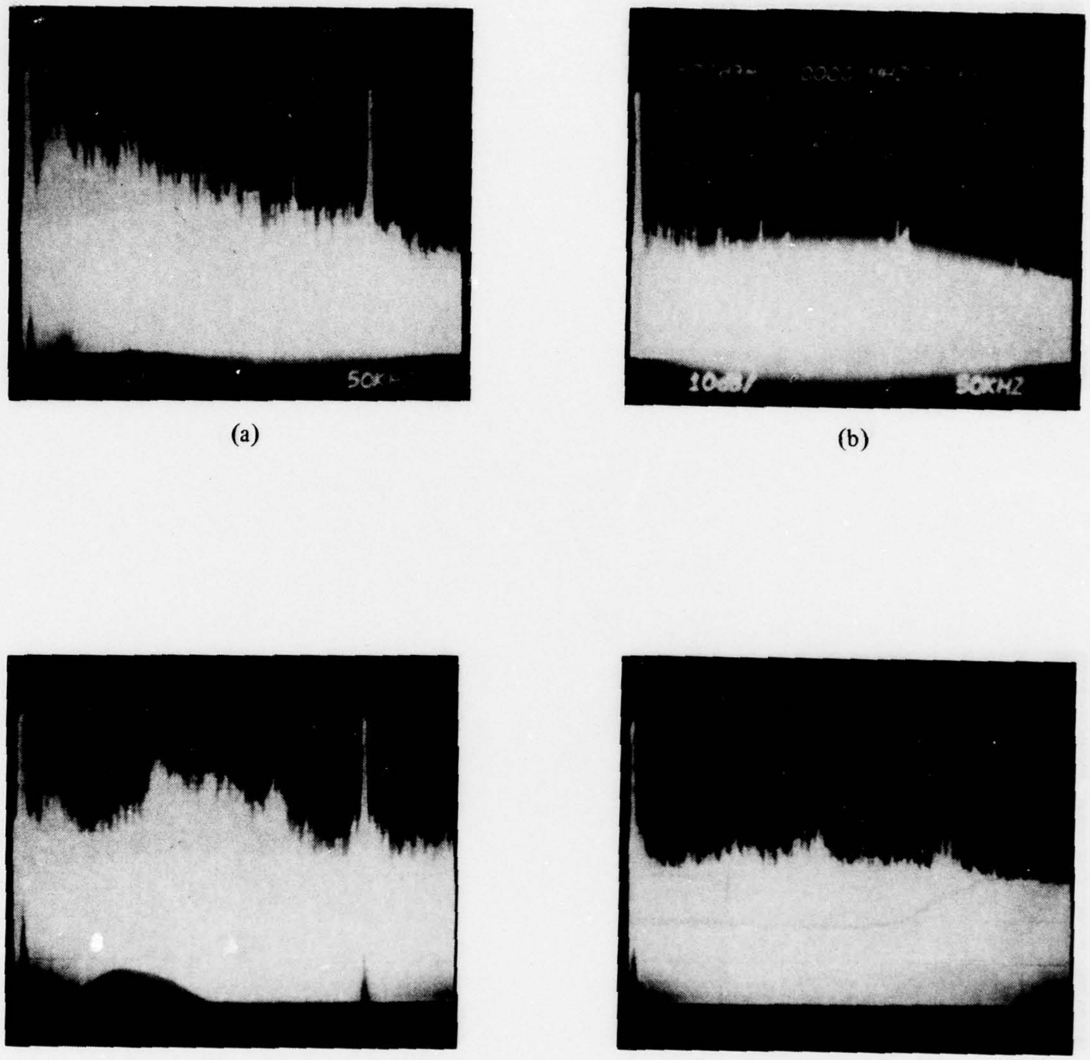
FIGURE 6. Spectrum Analyzer Displays of the Noise Levels on the Support of a Diesel Engine at Stand Speed. (a) 1-500 kHz and (b) 400-900 kHz using the AC175 transducer. (c) 1-500 kHz and (d) 400-500 kHz using the FC500 transducer. There are markers at 1 kHz and 400 kHz.



(a) (b)

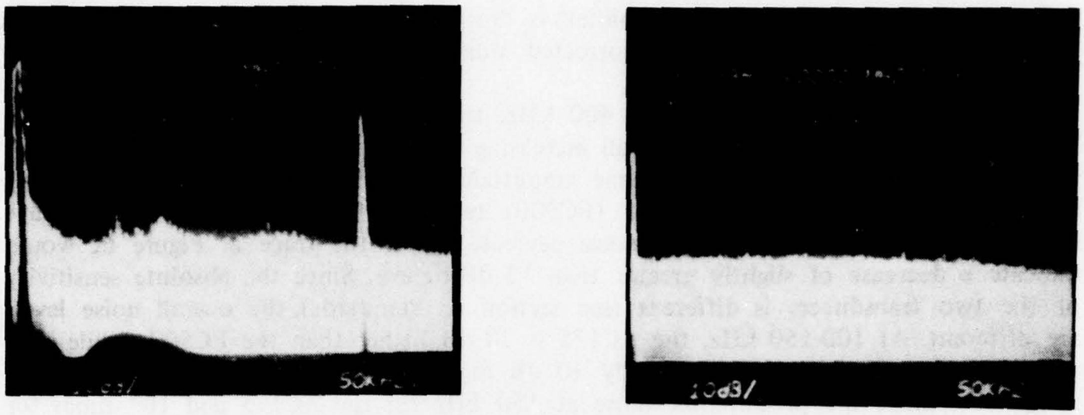
(c) (d)

FIGURE 7. Spectrum Analyzer Displays of the Noise Levels on the Support of a Gas Turbine at Stand Speed. (a) 1-500 kHz and (b) 400-900 kHz using the AC175 transducer. (c) 1-500 kHz and (d) 400-900 kHz using the FC500 transducer. There are markers at 1 kHz and 400 kHz.



(a) (b) (c) (d)

FIGURE 8. Spectrum Analyzer Displays of the Noise Levels on the Support of a Gas Turbine at Flank Speed. (a) 1-500 kHz and (b) 400-500 kHz using the AC175 transducer. (c) 1-500 kHz and (d) 400-500 kHz using the FC500 transducer. There are markers at 1 kHz and 400 kHz.



(a) (b)

FIGURE 9. Spectrum Analyzer Displays of the Noise Level on the Overhead One Compartment Forward of the Engine Room. (a) 1-500 kHz and (b) 400-500 kHz using the FC500 transducer. There are markers at 1 kHz and 400 kHz.

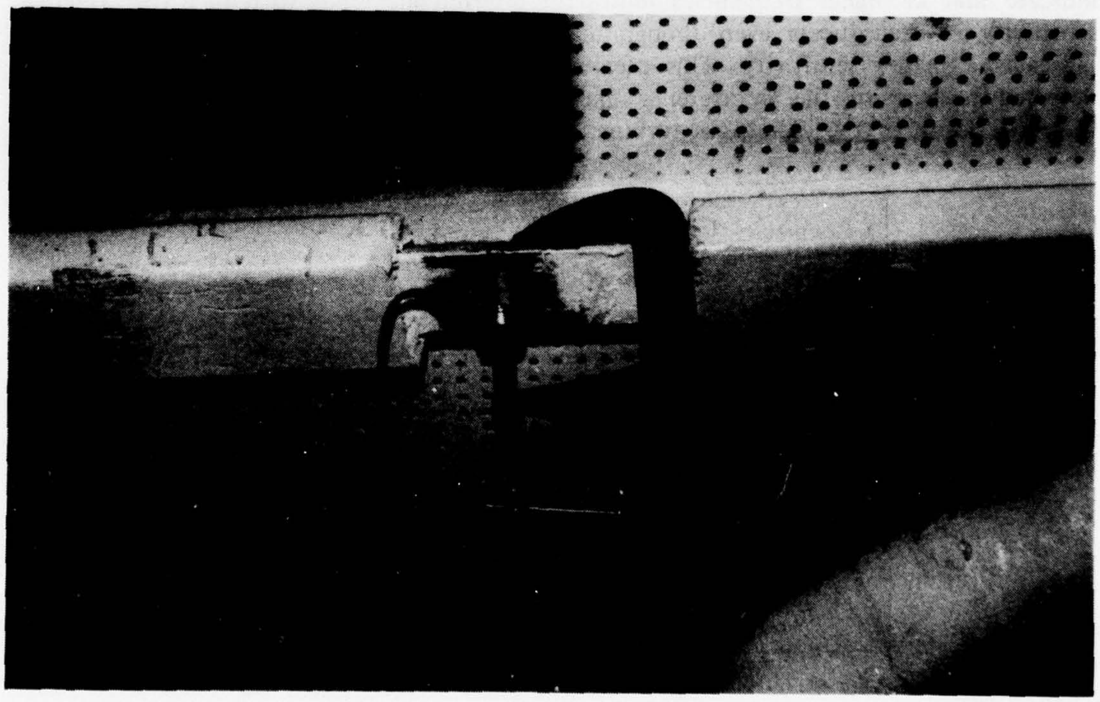


FIGURE 10. Transducer Mounted on an Overhead Beam Forward of the Engine Room.

decreasing as rap: lly as the preamplifier is "rolling off." Given that the transducer's sensitivity is alsc decreasing, the corrected noise level is increasing with decreasing frequency.

In the band from 100 kHz to 400 kHz, the preamplifier has a "flat" response. The FC500 transducer response is still increasing while the AC175 has several resonant peaks, each of approximately the same amplitude. In Figure 6a the noise is decreasing at 6 dB/octave and the transducer (FC500) response is increasing at 6 dB/octave indicating an overall 12 dB/octave noise decrease, while the trace in Figure 6c would indicate a decrease of slightly greater than 12 dB/octave. Since the absolute sensitivity of the two transducers is different (see section on standards), the overall noise levels are different. At 100-150 kHz, the AC175 is 20 dB higher than the FC500, while near 400 kHz, the AC175 is approximately 10 dB higher. These noise levels put the diesel about 10^4 times the preamplifier noise at 150 kHz for the AC175 and 10^3 times for the FC500. One must remember this is right on the engine support (away from the support, the level is down by two orders of magnitude or better).

Now looking at the levels for the gas turbine, Figures 7 and 8 show that between 100 and 400 kHz the turbine at standard speed is almost 3 orders of magnitude quieter than the diesel, and at flank speed it is only 2 times noisier than standard speed. At standard speed, the gas turbine is slightly quieter than the steam turbine.

Beyond 400 kHz, only the diesel has a significant amount of noise that is above preamplifier levels. However, measurements made in the laboratory on steel structures indicate that at higher frequencies multipath interference tends to reduce the effective sensitivity of transducers even though a face-to-face measurement of the transducers indicates a higher sensitivity. This means that there may be noise that is not being detected because of the interference and the preamplifier noise. Figure 11 compares the noise levels of the diesel, gas turbine, steam turbine and preamplifier.

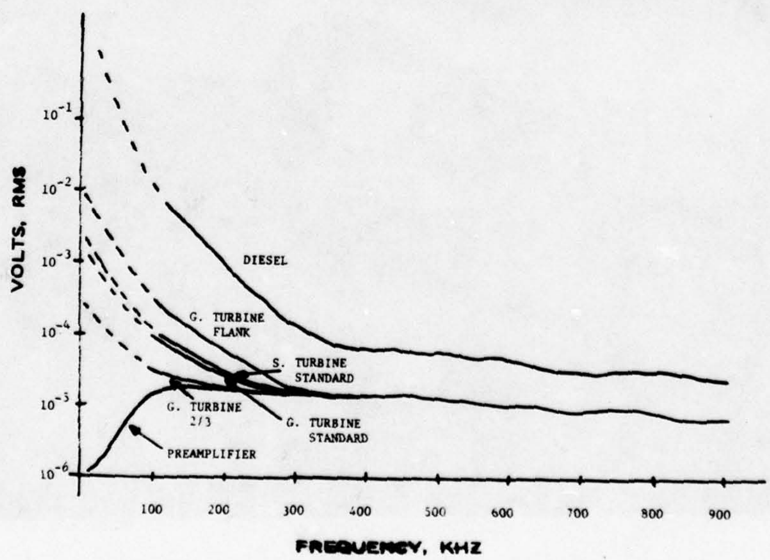


FIGURE 11. Comparison of Engine Noise Levels.

ATTENUATION AND MULTIPATH MEASUREMENTS

Attenuation and multipath interference were also measured on the ship. The equipment was set up as in Figure 12a. The voltage-control oscillator (VCO) was driven by a ramp generator which also drove the X axis of the XY plotter. By sweeping at a slow rate (2.0×10^{-3} Hz) multipath signals at each frequency have time to arrive at the receiver and interfere. The plots of Figure 13 are a representation of the multipath effects on amplitude versus driving frequency. These plots are not too useful, but do indicate that problems will occur in trying to use AM or FM modulation techniques without additional processing.

Another setup for looking at multipaths is shown in Figure 12b. Here received pulse stretching is examined. To observe the multiple path delays it is desirable to generate narrow pulses; however, the transducer "Q" causes "ringing" that extends the pulse so that only the first few arrivals are separable. Pulse widths of 30 to 100 microseconds were obtainable. This was sufficient to separate the first two or three arrivals. It is possible to qualitatively say that, for short paths, the pulse spread was less and that, for more complex structures with many beams and plates coupled to the main path, the pulse spread was approximately 10 to 20 microseconds. This limits the maximum data rate to 50 to 100 bits per second without special processing.

LABORATORY MEASUREMENTS

Since ships are not readily available for testing and data gathering, another structure, the laboratory building, steel framework was used. The structure is slightly different from that of the ship: lower noise, lower attenuation, and slightly greater multipath interference. But if these differences are known, the ship performance can be related to laboratory measurements in a predictable fashion. The effect of the shipboard noise can be taken into account by scaling the measured signal-to-noise ratio. The attenuation can be simulated by working over longer distances. With the lower attentuation of the building, the multipath interference is worse. Under this condition, solutions that work on the building should work better on the ship.

MULTIPATH INTERFERENCE

After accomplishing data transmission over the building structure, an attempt was made to characterize the multipath interference. The same setup as Figure 12a was used. The plot in Figure 14 is similar to Figure 13. However, if either transducer is moved the plot changes. If the frequency is varied the plot changes. If neither location nor frequency change but some change occurs in the path, the plot will change. This kind of sensitivity to the medium is undesirable and rules out simple AM or FM data transmission. The position sensitivity can be reduced by several methods including either modulating a linear FM sweep or modulating band-limited noise. Both methods have been tried and both reduce the sensitivity to less than 6 dB over the beam area near the receiver.

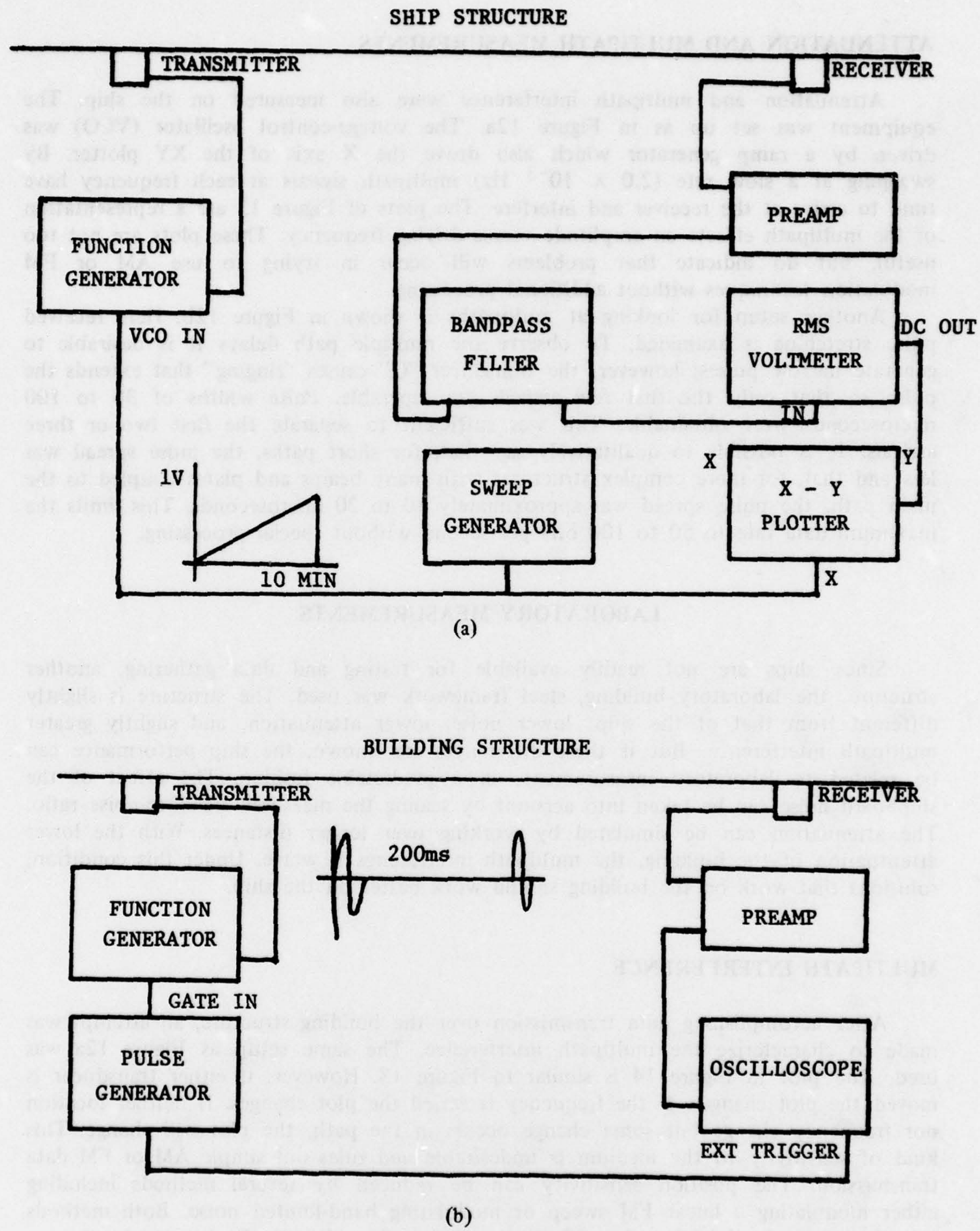
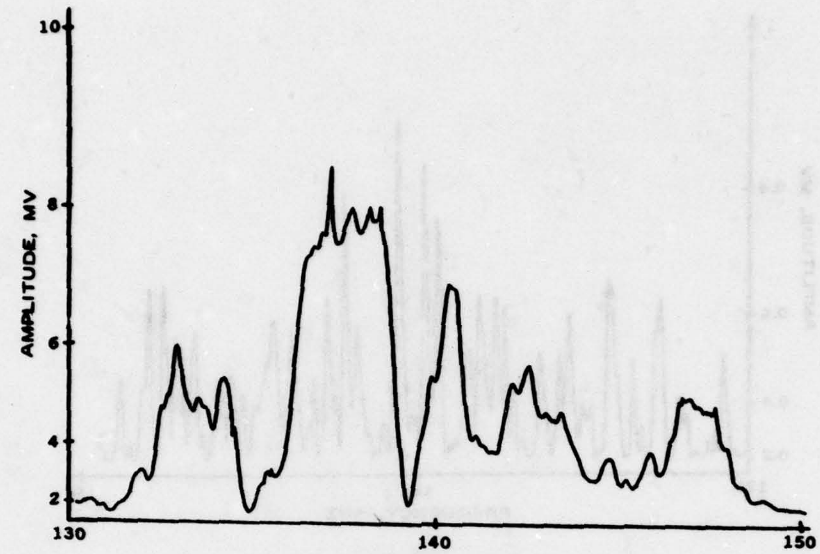
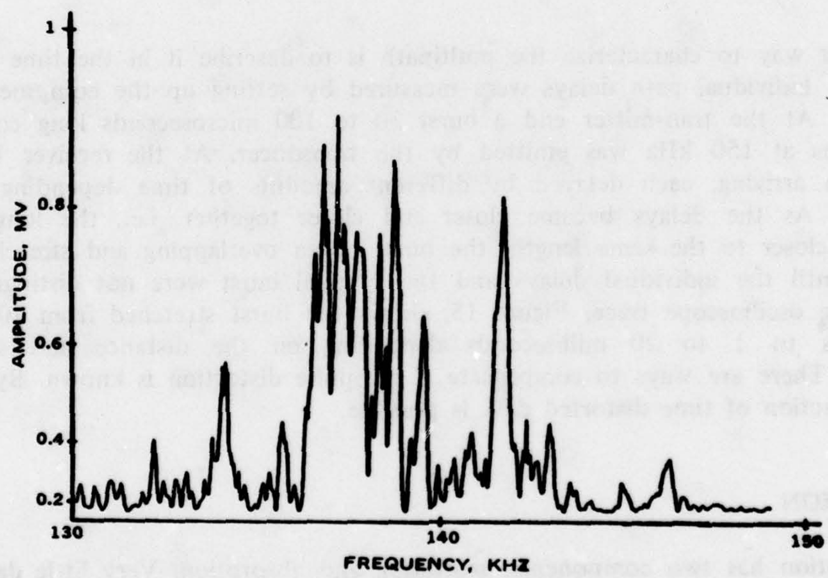


FIGURE 12. Methods of Measuring Multipath Interference: (a) FM sweep, (b) pulse delay.



(a)



(b)

FIGURE 13. Multipath Interference Effects. (a) Over a 30-foot path, (b) over a 15-foot path to a loosely mounted hatch.

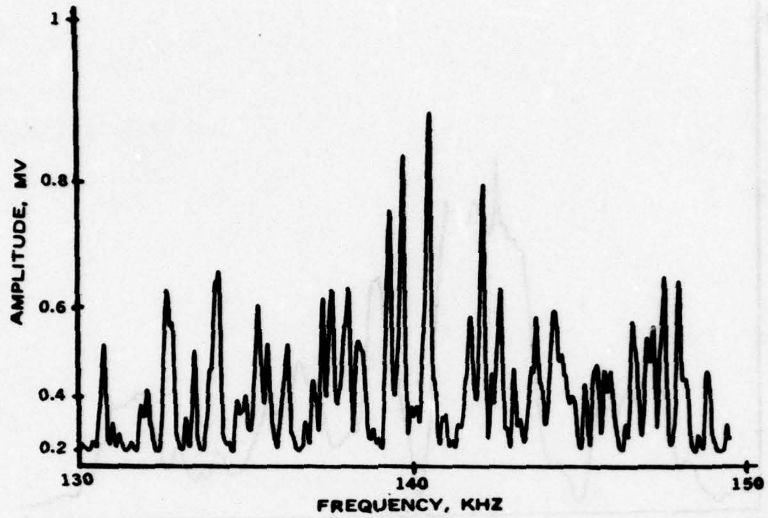


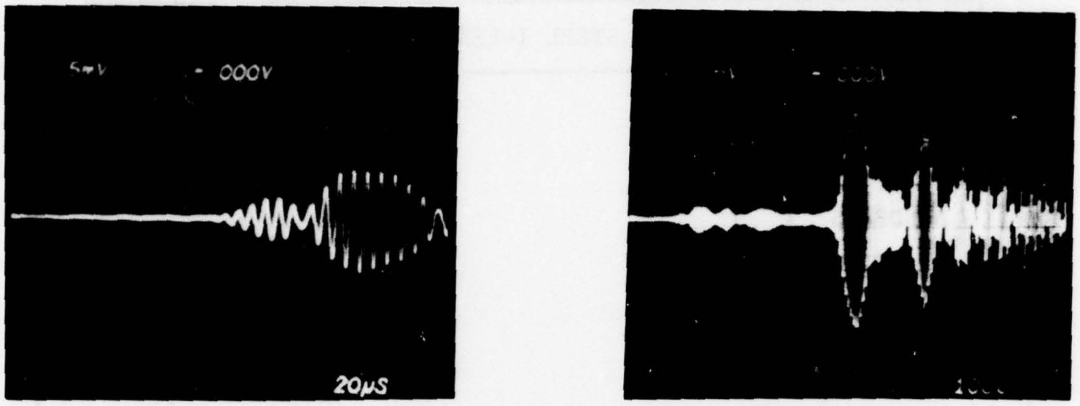
FIGURE 14. Multipath Interference Effects for a 50-foot Path Through the Laboratory Building Structure.

Another way to characterize the multipath is to describe it in the time domain. To do this, individual path delays were measured by setting up the equipment as in Figure 12b. At the transmitter end a burst 30 to 100 microseconds long containing several cycles at 150 kHz was emitted by the transducer. At the receiver 150 kHz bursts began arriving, each delayed by different amounts of time depending on the path taken. As the delays became closer and closer together, i.e., the longer path lengths are closer to the same length, the burst began overlapping and stretching out the pulse until the individual delays and the original burst were not distinguishable. The resulting oscilloscope trace, Figure 15, shows the burst stretched from 30 to 100 microseconds to 1 to 20 milliseconds depending on the distance and structure complexity. There are ways to compensate if the pulse distortion is known. By proper coding, extraction of time distorted data is possible.

ATTENUATION

Attenuation has two components, scattering and absorption. Very little data exist in the literature. Most authors are interested in higher frequencies and no one addresses complex real structures. According to Mason,[2] the absorption increases with frequency but extracting data for steel from his graphs is difficult between 100 kHz and 1 MHz. Also, measurements of the values for steel are difficult to make due to multipath effects. (In this range, aluminum has a value of 0.1 to 0.2 dB per foot depending upon the grain size and frequency.)

To obtain attenuation measurements, the equipment was set up again as shown in



(a) (b)

FIGURE 15. Pulse Stretching Due to Multipath. (b) is an expansion of the first two group arrivals in (a).

Figure 12a. Steel rods of different lengths were used because of their simple geometry. The first problem that arose was that of coupling to the rod in a manner that would be consistent from rod to rod. The most consistent method seemed to be bonding with Eastman 910 adhesive. However, that made removing the transducer difficult.

Band limited noise was then tried as a source. The setup is shown in Figure 16. Here the RMS voltage for different bands and different lengths of steel rod are compared. The results are shown in Table 1. Table 1 indicates that the absorption is between 0.13 and 0.27 dB per foot, increasing with frequency and length. There are still questions to be answered about this method.

An interesting result came from these measurements while working with several types and sizes of transducers. It was discovered that when a transducer is coupled using oil and is cocked slightly so that its effective area is reduced, more voltage is measured at the output. Also, if a smaller diameter (3/8-inch compared to 3/4-inch) transducer with the same sensitivity is used, an even higher output results. This means that the transducer sensitivity is also size dependent when coupled to complex structures as was the case when the ship noise measurements were made. This effect also seemed more pronounced at higher frequencies which would indicate that more sensitivity can be obtained at higher frequencies using smaller diameter transducers.

The reason for the increase in received signal amplitude can be seen by plotting the amplitude and phase of the acoustic wave component normal to the surface in the area of the receiver. This was accomplished by using a probe such as in Figure 17 and by using the setup shown in Figure 18. The amplitude peaks do not have the same phase. In fact, they may have completely opposite phases as diagrammed in Figure 19.

A transducer constructed from many small elements all connected in parallel as in Figure 20a would have the same output as a single transducer of the same area. However, if the outputs of each small transducer were taken separately they would have different phases and amplitudes corresponding to the peaks and valleys of Figure 19. In parallel, they would have an average value, separately, a peak value. If the sinewave source is replaced by a noise source, the amplitude variations decrease because the coherence has decreased.

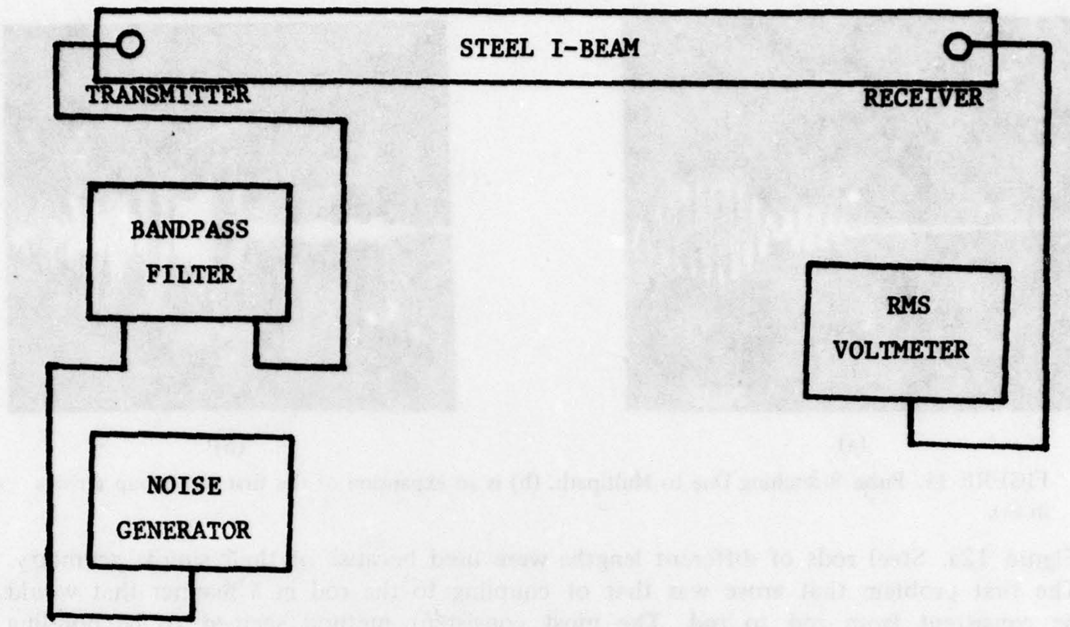


FIGURE 16. Attenuation Measurements Using Band-Limited Noise.

TABLE 1. Ultrasonic Attenuation in Steel Rods.

Frequency, kHz	Attenuation, dB/ft
130-150	.13
150-170	.19
210-230	.22
230-250	.23
300-350	.27

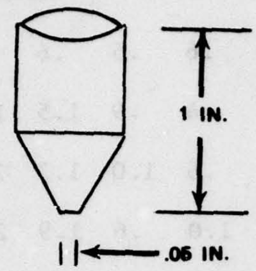


FIGURE 17. Ultrasonic Probe.

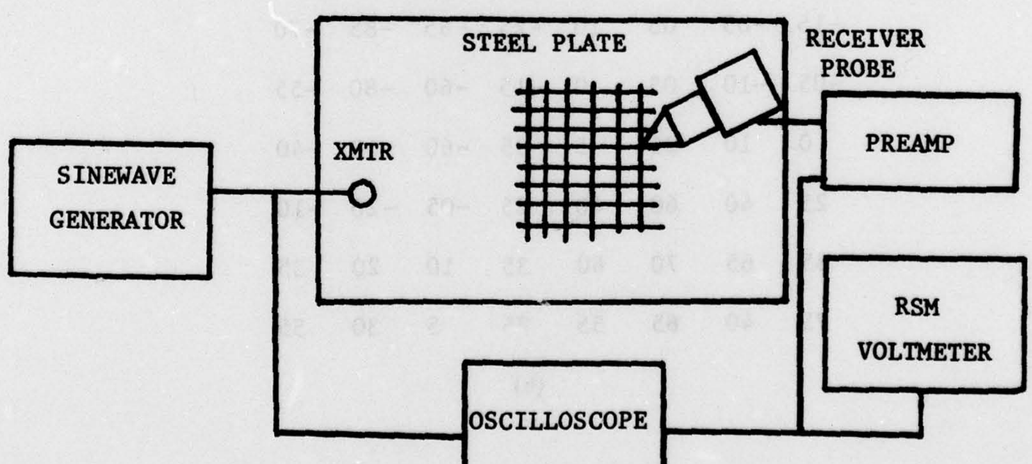


FIGURE 18. Surface Ultrasonic Wave Pattern Test Setup.

.8"

1.3	1.4	1.2	.6	.5	.6	.9	1.9
1.7	1.5	.7	.4	.9	1.5	1.9	2.0
1.2	1.2	1.1	.6	1.0	1.7	2.7	1.7
1.3	1.2	1.3	1.0	.6	1.9	2.6	1.4
1.5	1.9	1.6	1.8	1.5	.5	.9	1.0
1.0	1.4	1.9	.2	1.8	.8	.1	.4
0.5	0.9	1.4	.1	.2	.7	.1	.1
0.7	1.0	1.1	.9	.5	.8	.3	.4
0.9	1.3	1.6	1.7	1.4	1.2	.8	.9

.8"

(a)

-05	20	55	35	-10	-35	-75	-60
0	10	25	55	05	-35	-75	-75
-15	-05	05	10	-25	-65	-85	-70
-05	-10	05	0	-15	-60	-80	-55
0	10	25	5	-35	-60	-60	-40
25	40	60	40	25	-05	-20	-10
35	65	70	60	35	10	20	35
75	40	65	55	25	5	30	55

(b)

FIGURE 19. (a) Amplitude map of an ultrasonic wave pattern at the surface of an aluminum plate over an .8-inch by .8-inch area. (b) Phase map of the same area. All values are in degrees.

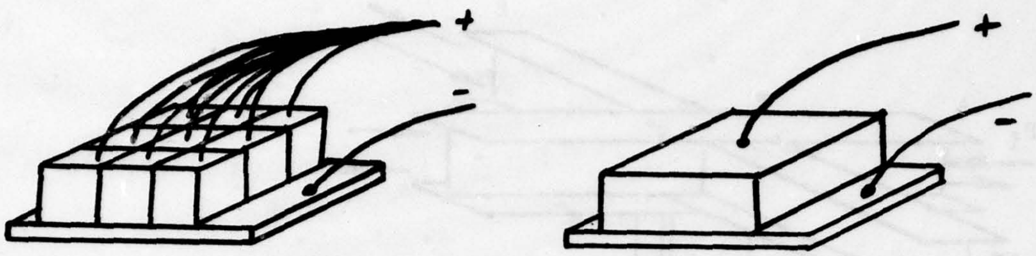


FIGURE 20. A Multi-Element Transducer and a Single Element of the Same Area.

SCATTERING

Figure 21 depicts an intersection of beams that are welded together. A multimode pressure wave, P_i, traveling down beam A, will decrease in amplitude from scattering losses to beams B, C, and D. Some of the energy that is lost may be reflected back when additional boundaries are encountered or it may take a path that leads to the intended receiver and add to the multipath interference. In Figure 21b, the wave, P_i, entering the beam may be scattered throughout the attached steel plate. These types of boundaries are found throughout a ship. The amount of energy transmitted to its destination and the multipaths taken (or the amount of reflection and scattering) varies with the boundary conditions. The quality of a weld, the amount of paint or rust, the size and shape of the structure, and roughness of surfaces all affect the modes generated and the amount of scattering.

Attempts to direct the energy along a preferred path have been unsuccessful because of the variations in the structure causing mode conversion, scattering, and reflections. Beam dimensions on the order of a wavelength cause mode conversion within a few feet of the source. Because of the many variations, it is impossible to predict the attenuation in general. Table 2 is a list of attenuation for several paths in the building and aboard ships. Generally, the attenuation aboard ship is 30 dB higher for the same path length.

COUPLING

The problem of coupling the acoustic energy into and out of the structure was investigated in the laboratory and aboard ship. A reliable method was needed for both temporary and permanent coupling. There are several articles in the literature on couplants, mounting fixtures, and couplers such as wedges. Several methods proved useful. For temporary coupling, an oil or water film provided consistent coupling with a slight amount of pressure provided by a C clamp or magnetic clamp. For permanent installation, a combination of a cement such as Eastman 910 or an epoxy and a clamp

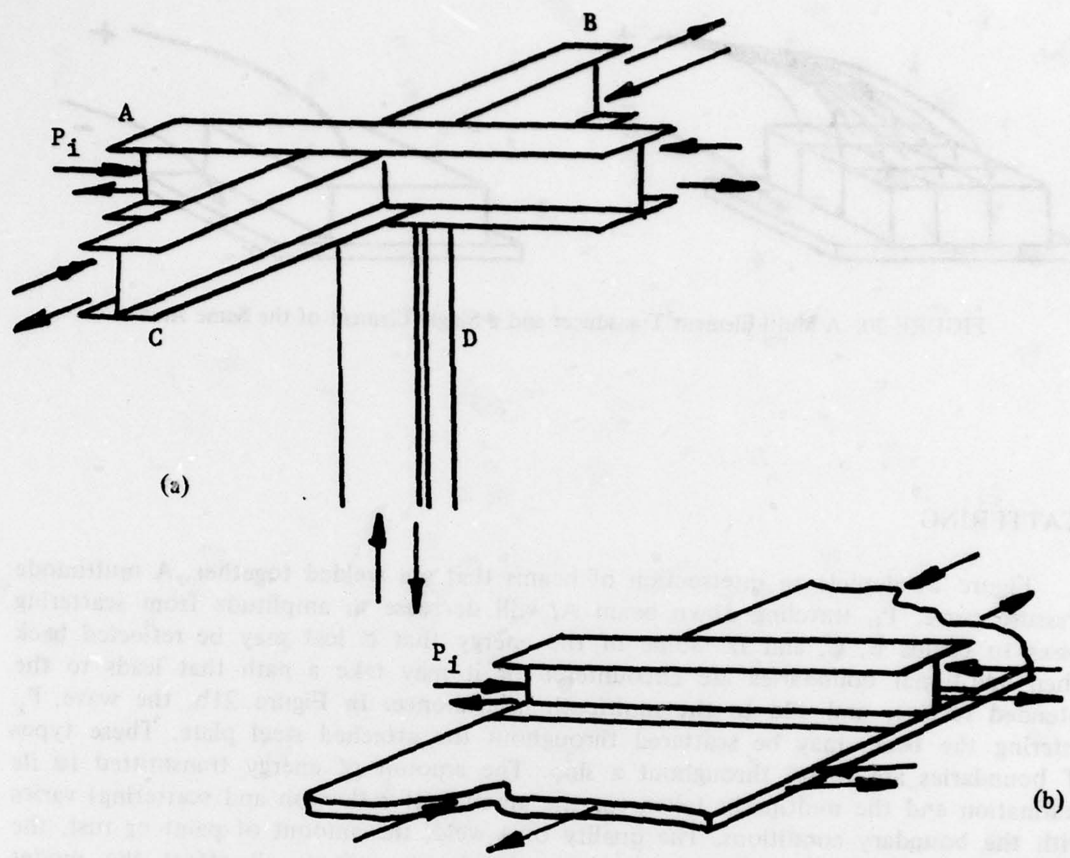


FIGURE 21. Scattering of Ultrasonic Waves in Steel Structures.

TABLE 2. Ultrasonic Attenuation for Several Paths.

Path	Attenuation, dB
50 ft of building steel structure	25
115 ft of building steel structure	115
55 ft of ship steel structure	85

or some kind of protection was sufficient. (Before coupling to either a heavily or poorly painted surface, the paint should be scraped off and the surface sanded.)

An attempt was made to improve signal strength, reduce multipath interference and provide directionality. A separately funded program addressed this problem. Several promising coupler shapes and materials were tried. None seemed to provide any improvement when used at the source. Transmitter arrays were useful in improving signal strength, however. Controlling the phase relationship between the elements caused fluctuations at the receiver similar to those mentioned earlier when the frequency was varied. Sonar arrays have been studied and have shown usefulness, but more work needs to be done for this application.

At the receiver, some improvement was noted, as discussed before, by using smaller detector areas. The acoustic signal seemed to have an even distribution of energy among the many modes generated before reaching the receiver. Trying to couple out specific modes did not increase the signal. Since the piezoelectric transducers are not energy- or power-sensitive devices but are linear with the applied pressure, collecting more modes over larger areas only tends to decrease the signal because of the differing phases.

SHIP DAMAGE-CONTROL LINK CONCEPT

The original damage-control ship-data-link concept had a central controller, with each fire sensor or warning device reporting to the central controller. This concept was vulnerable to damage to the central controller and required links to cover distances up to half the ship's length or better. A new concept which decentralizes the system, allowing each damage control station (DCS) to operate independently of damage control central (DCC), if necessary, has been formulated. Such a system would also reduce the requirement for long distance transmission and make it compatible with other proposed ship communications systems.

Figure 22 is a block diagram of a portion of the concept. The individual sensors would send data to a DCS (or some other convenient location). The DCS then would send data to and be controlled by the DCC. If the DCC became inoperative, each DCS would continue to perform built-in tests and continue monitoring of the sensors under its own control. Sensor status would be displayed at both locations: the DCS and DCC. When a sensor alarm occurred, the sensor would send an interrupt to the DCS which in turn would alert the DCC and would begin a built-in test sequence to determine if, indeed, an alarm had occurred. If the sensor failed the built-in tests, the DCS would send data describing the type of failure and its location. If the sensor passed the built-in tests, the DCS would send an alarm along with the type of alarm (fire, high temperature, high or low pressure, or water level) and its location. The information would then be displayed for the damage control officer at the DCC and for damage control parties at the DCS. If the DCC became inoperative, the information would be available at each DCS in that area.

This approach also fits in with other data bus concepts. If a data bus exists, the DCS and the DCC become terminals and instead of the link between the DCC and each DCS being an acoustic link, it would be part of the data bus. If the data bus

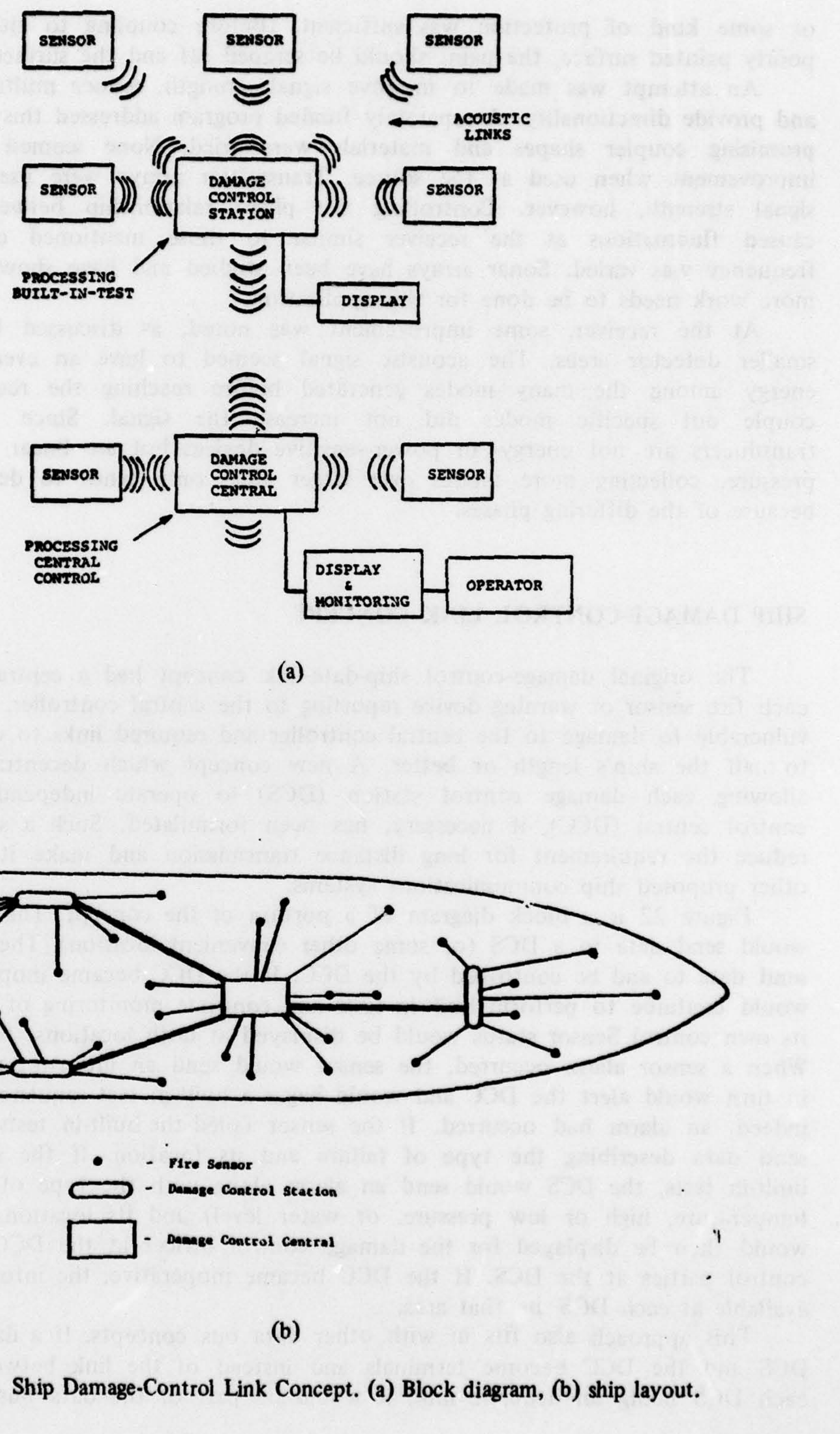


FIGURE 22. Ship Damage-Control Link Concept. (a) Block diagram, (b) ship layout.

became overloaded or inoperative, each DCS could then operate independently so that protection is not lost.

VOICE COMMUNICATIONS

During the last thirty years several investigators have developed voice coding schemes to reduce the bandwidth required for digitized voice.[6,7] Ordinarily digitized voice requires bit rates up to 30 kbits/s. Work done by Slaymaker[7] indicates that coded speech bit rates as low as 25 bits/s are possible. At the 1976 IEEE Conference on Acoustics, Speech and Signal processing, Kang and Coulten reported on a 600 bit/s voice digitizer that used predictive techniques. Interestingly, Texas Instruments, Inc., has recently developed a speech-synthesizing integrated circuit that requires 1133 bits/s and is used in a fifty-dollar educational toy.

These recent developments have brought the reality of an ultrasonic voice link much closer. Additional signal processing, such as compensating for multipath delays that distort pulses and reduce the data rate, can make voice communications via ultrasonics through the ship structure possible.

CONCLUSIONS

BACKGROUND NOISE

Three types of engines were measured for ultrasonic noise: diesel, steam turbine and gas turbine. The noise levels below 100 kHz for all types were increasing at about 12 dB per decade. If the transducer sensitivities can be assumed to be absolute, then at 100 kHz the diesel RMS-noise pressure level was 56 microbar or 10 millivolts RMS at the output of the preamplifier using the AC175 transducer. This compares to the turbines at standard speed with noise levels of 0.3 microbar and 50 microvolts at the preamplifier output, or 500 times quieter than the diesel. Even at flank speed (top speed) the gas turbine is 250 times quieter.

Above 100 kHz, the noise from all engines decreases, but above 300 kHz, the turbine noise is about the same as the preamplifier. The diesel noise, however, does not level off until 400 kHz and the level is 2 to 3 times the preamplifier noise. Away from the engines, noise levels are very close to the preamplifier noise level. There are noise spikes that occur randomly due to impacts with the ship structure such as sailors jumping down ladders, tools or heavy objects being dropped, or chipping hammers being used near the transducer. None of these sources present any difficult processing problems, however.

[6] Flanagan, James L. "A Resonance-Vocoder and Baseband Complement: A Hybrid System for Speech Transmission." *IRE Transactions on Audio*, Vol. AV-8, No. 1, May-June 1960, pp 95-102.

[7] Slaymaker, Frank H. "Bandwidth Compression by Means of Vocoders." *IRE Transactions on Audio*, Vol. AV-8, No. 1, January-February 1960, pp 20-26.

ATTENUATION

It was concluded that most attenuation is due to scattering. Only 0.1 dB to 0.2 dB per foot is due to absorption. The amount of scattering is dependent on how the structure is held together and on how many adjoining structures there are. Two paths of the same length do not necessarily have the same attenuation. Attenuation ranged from 0.5 dB per foot for a short path to 1.0 dB per foot for a 115-foot path in the laboratory to 1.5 dB per foot for a 55-foot path on the ship. These attenuations should allow transmission distances up to 150 feet.

MULTIPATH INTERFERENCE EFFECTS

Within any complex structure, ultrasonic waves traveling through it experience many mode conversions that occur at the boundaries. The result is that the ultrasonic waves take many different paths of different lengths. Since not all the waves arrive at the same time with the same phase, there is interference and also a narrow, well-defined pulse transmitted through the structure is stretched 10 to 20 milliseconds wide. This limits the maximum data rate for most simple modulation schemes to 50 to 100 bits per second. A complex scheme could increase the data rate at a sacrifice of low cost. Two methods of modulation that reduced the position and frequency sensitivity (which result from the complex surface wave pattern at the receiver due to multipath) are a linear FM sweep and band-limited noise pulse.

COUPLING

Several coupling schemes borrowed from the acoustic emission technology area were useful for coupling to the ship. For temporary coupling, a C clamp or magnetic clamp with a film of oil as a couplant gave repeatable results. For permanent coupling, an epoxy or Eastman 910 was useful. Attempts to obtain directionality were unproductive due to the many mode conversions that occurred in complex structures. Directionally sensitive transducers did not provide any gain in signal. An improvement of a 2- to 3-times greater signal was obtained with a smaller area transducer with the same signal sensitivity as the larger transducers. This was a result of averaging over a single peak in the surface wave pattern at the receiver, instead of averaging over many "out-of-phase" peaks.

Appendix A

PHOTOGRAPHS OF TRANSDUCERS MOUNTED ON THE ENGINE SUPPORTS OF A GAS TURBINE AND A DIESEL ENGINE

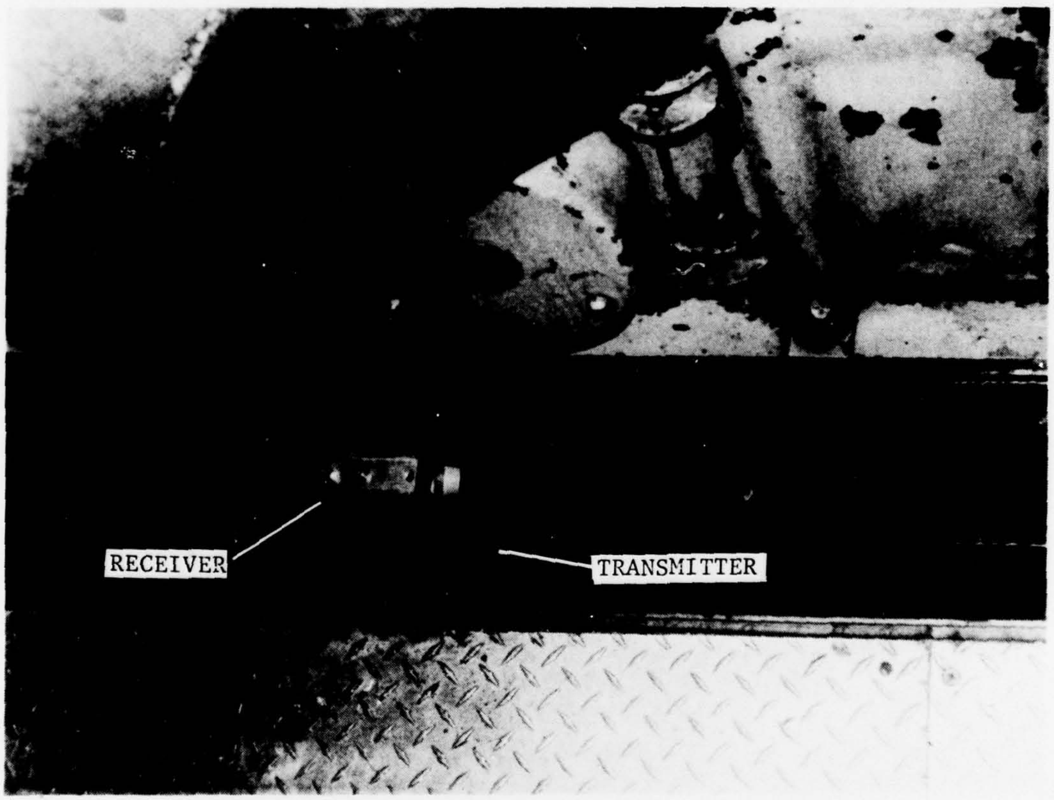


FIGURE A-1. The receiving transducer was located on the support frame of a diesel engine near the exhaust pipe (the large tube in the upper left hand corner) while the transmitting transducer (used to check coupling quality) was located under the support (see Figure A-2.)

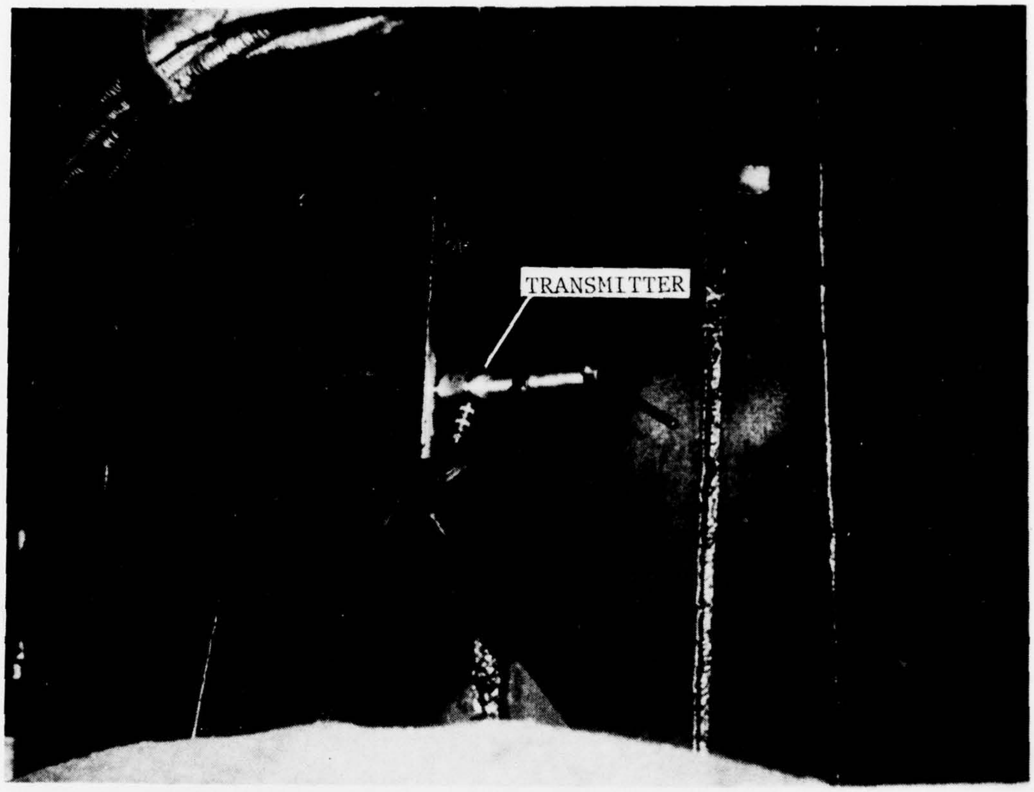


FIGURE A-2. The transmitter was used to check coupling and as a frequency marker when using the spectrum analyzer.

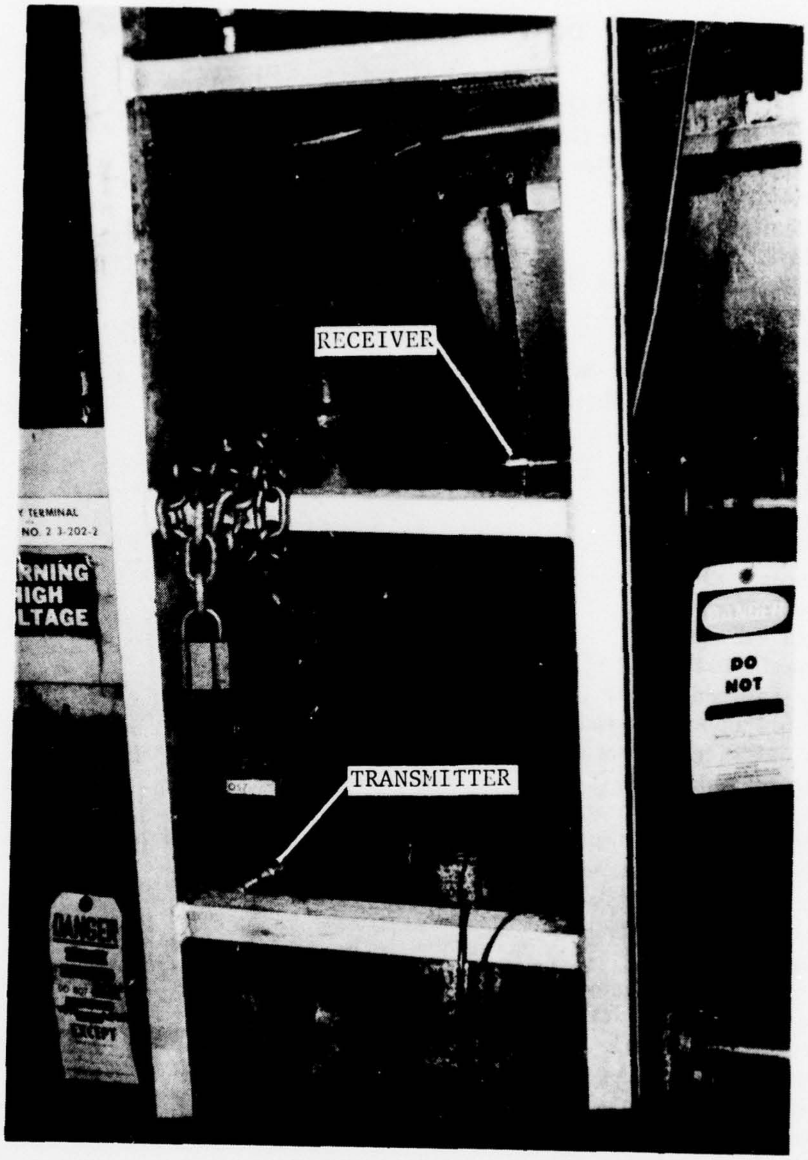


FIGURE A-3. Location of the Receiver and Transmitter for the Measurements on the Gas Turbine. This support is located directly below the combustion chamber.

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